Ultraviolet Light Disinfection in the Use of Individual Water Purification Devices

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PURPOSE

This information paper provides an in-depth review of ultraviolet (UV) light for use as a disinfection technology in potable water supplies. This paper is intended to assist the reader in evaluating the disinfection capabilities of UV light-using Individual Water Purification Devices (IWPDs) to inactivate disease-causing bacteria, viruses, and cysts.

REFERENCES

Appendix A contains a list of references.

INTRODUCTION

Background

Understanding the disinfection capabilities of UV light to inactivate disease-causing microorganisms is important in protecting Soldiers, who are considering using this technology, from acute health threats posed by these microorganisms. Soldiers deployed beyond traditional field drinking water supplies must have access to microbiologically safe water. Using IWPDs is one way to provide microbiologically safe water in these situations. These IWPDs must protect the Soldier from acute microbial health threats. The U.S. Environmental Protection Agency (EPA) Guide Standard and Protocol for Testing Microbiological Water Purifiers (reference 1) provides performance standards by which an IWPD that uses UV light can be evaluated. The performance standards are a minimum 6-log reduction/inactivation of bacteria, 4-log reduction/inactivation of viruses, and 3-log reduction/inactivation of protozoan cysts. UV-using IWPDs meeting these standards are considered effective against disease causing bacteria, viruses, and protozoan cysts. Some IWPD manufacturers test their devices using this protocol. This is the best way to evaluate the IWPDs disinfection capabilities. In the absence of that testing data, this information paper can be used to gain an understanding of UV light disinfection capabilities and help determine if an IWPD using UV light could successfully meet the EPA Guide's minimum performance standards. This information paper was developed primarily using information obtained from the EPA's Draft Ultraviolet Disinfection Guidance Manual (reference 2). The manual provides a comprehensive review of available scientific literature concerning UV disinfection in drinking water systems.

b. History of UV Light in Potable Water Applications. The germicidal properties of UV light were discovered in 1887. The first application of UV light in drinking water occurred in

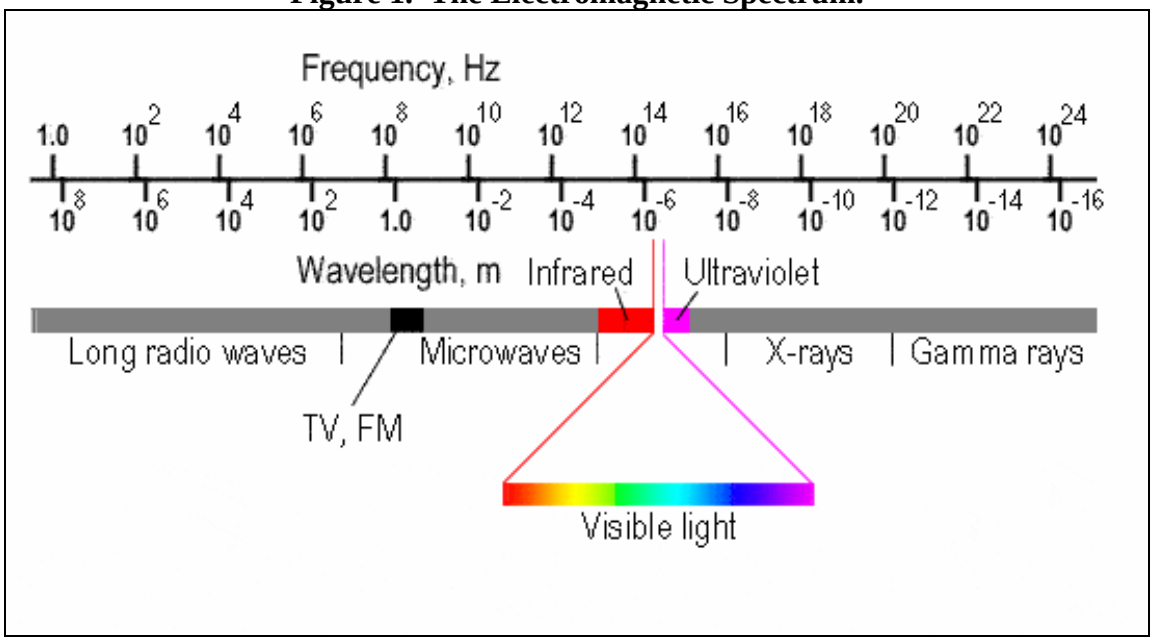
1910 at Marselles, France. Since then, UV light is used in drinking water systems worldwide primarily for disinfection. Currently there is only one Commercial-Off-The-Shelf (COTS) IWPD using UV light for disinfection. However, as UV research continues, more COTS IWPDs incorporating UV technology may be developed.

ULTRAVIOLET DISINFECTION

UV Light Description

In drinking water, UV light is used for disinfection. The use of UV for disinfection involves: (1) the generation of UV light with the desired germicidal properties, and (2) the delivery (or transmission) of that light to microbial pathogens. As Figure 1 shows, UV light lies between x-rays and visible light in the electromagnetic spectrum. The UV spectrum covers the wavelength range from 100-400 nm. UV light at certain wavelengths can inactivate microorganisms. UV light with wavelengths from 200-300 nm inactivates most microorganisms, with the greatest amount of inactivation occurring around 260 nm.

Figure 1. The Electromagnetic Spectrum.



Source: http://www.sentinelarchiving.com/ARTICLES/electromag.htm

UV Light Generation

Generation of UV light is similar to the generation of light in a fluorescent lamp. In general, a UV lamp contains an inert gas (e.g., argon) and a small amount of liquid mercury. When a

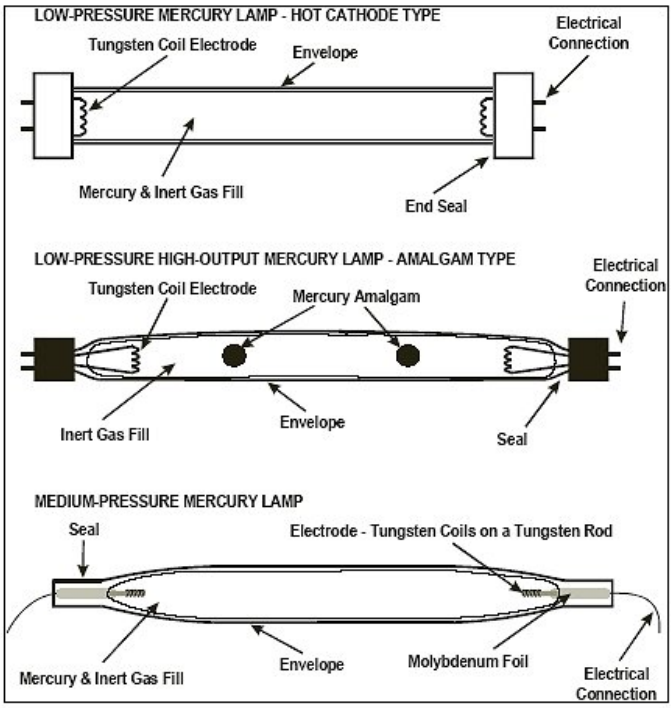
voltage is applied to the lamp, some of the liquid mercury vaporizes. Free electrons and ions then collide with the gaseous mercury atoms, "exciting" the mercury atoms into a higher energy state. Excited mercury atoms have a tendency to return to their ground, or normal, energy state by discharging energy. The energy discharged is in the form of UV light. Mercury is advantageous for UV disinfection applications because it emits light in the germicidal wavelength range (200 – 300 nm). The UV light produced depends on the concentration of mercury atoms in the UV lamp, which is directly related to the mercury vapor pressure. Low pressure mercury vapor produces monochromatic (light at primarily one wavelength) UV light at a wavelength of 253.7 nm. Higher pressure mercury vapor produces UV light at several wavelengths (polychromatic).

UV Lamps

UV Lamp Types

For water treatment systems, there are three general types of UV lamps typically used; low-pressure (LP), low-pressure high-output (LPHO), and medium-pressure (MP). These terms are based on the vapor pressure of mercury when the lamps are operating. LP and LPHO lamps operate at mercury vapor pressures of $2x10^{-3}$ – $2x10^{-5}$ pounds per square inch (psi), thereby producing monochromatic UV light at 253.7 nm. MP lamps operate at much higher mercury vapor pressures of 2 – 200 psi and produce polychromatic UV light at a higher intensity. LP and LPHO lamps operate at temperatures of 40 – 200° C, while MP lamps operate at a much higher temperature range of 600-900° C. LP lamps have the lowest power requirements, while LPHO and MP lamps have higher power requirements. Subsequently, LP lamps have the lowest germicidal output (0.2 W/cm), while LPHO and MP lamps have higher germicidal outputs (0.5 – 3.5 W/cm and 5 – 30 W/cm, respectively). Figure 2 shows drawings of LP, LPHO, and MP lamps. There is generally no difference in disinfection capability between these lamps. But there are advantages and disadvantages to each. For example, compared to LP lamps, MP lamps have a higher germicidal output, typically require fewer lamps for a given applications, and would likely be a smaller reactor. There are other types of lamps that can produce UV light such as metal halide lamps, electrode-less mercury vapor lamps, and eximer lams. However, because these lamps are not commonly used for drinking water UV disinfection application, they are not discussed here. Most UV-using IWPDs will likely use LP lamps due to lower operating temperatures and lower power requirements.

Figure 2. LP, LPHO, and MP Lamp Drawings.



Source: Reference 2

UV Lamp Breakage

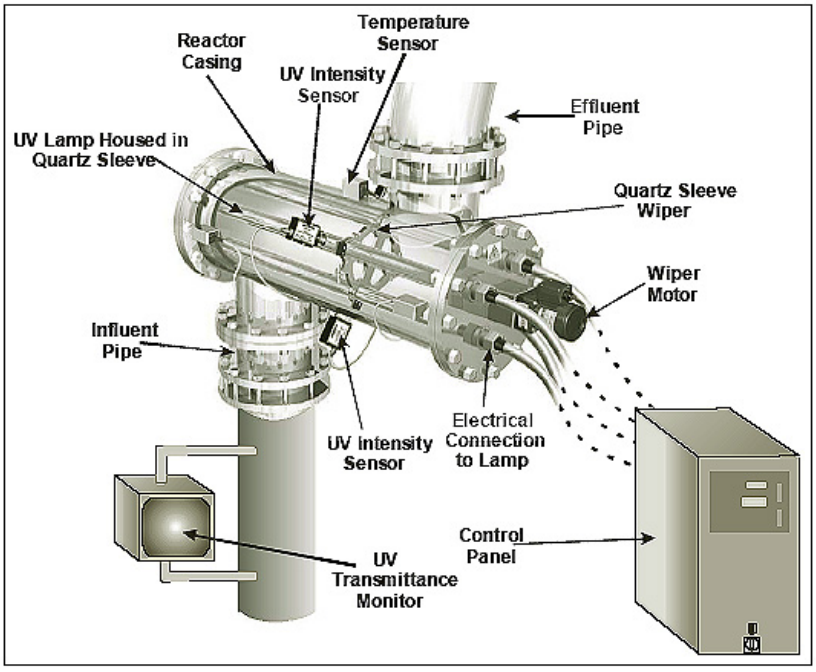
Lamp sleeves can break. Breakage is a concern due to potential for mercury release. UV lamps contain mercury or an amalgam composed of mercury and another element, such as indium or gallium. LP and MP lamps generally contain elemental mercury, while LHPO lamps generally contain a mercury amalgam. The mercury contained within a UV lamp is isolated from exposure by a lamp envelope and surrounding lamp sleeve. For the mercury to be released, both the lamp and lamp sleeve must break. Breakage can occur when lamps are in operation as well as when not operating but during maintenance. The mercury content in a single UV lamp used for water treatment typically ranges from 0.005 to 0.4 grams (5-400 mg). LP lamps have less mercury (5-50 mg/lamp) compared to LPHO (26-150 mg/lamp) and MP lamps (200-400 mg/lamp). Depending on the state mercury is in (gas, solid, or liquid) when a lamp breaks can be important when determining potential health risks. Mercury in the vapor phase may be released as very fine particles, which may readily dissolve in water, as opposed to solid or liquid mercury that will tend to settle. There is very little information on determining the amount of mercury released relative to the amount of mercury in the lamp prior to breakage. One study involving the breakage of a UV lamp containing 150 mg mercury in a 50 L batch reactor resulted in a concentration of 2.5 ug/L of mercury in the reactor. However, it was not reported whether all

150 mg of mercury was recovered. For IWPD use, since it is assumed that LP lamps are used, breakage of the lamp during operation may result in contamination of water being treated with 5-50 mg of mercury.

UV Reactors

In drinking water systems, UV lamps are contained in a UV reactor. UV reactors operate as either batch or continuous flow reactors. Several characteristics must be taken into account when designing, installing, and operating a UV reactor. Among them are water quality characteristics, distance between the lamp and the reactor wall, and the distribution of UV light. Additionally, continuous flow reactors must take into account hydraulic characteristics of water flowing through the reactor. Due to all these characteristics, microorganisms will not all receive the same UV dose. For example, UV lamp placement in a reactor influences UV dose delivery. If the distance between the lamp and the reactor wall is too large (i.e., a large amount of water between the lamp and the reactor wall), microorganisms furthest from the lamp will receive less UV intensity and subsequently a lower UV dose. Figure 3 is a schematic of a continuous flow UV reactor. Most UV-using IWPDs will likely utilize a batch reactor system.

Figure 3. Continuous Flow UV Reactor Schematic.



Source: Reference 2.

UV Dose

Definition of UV Dose

In drinking water applications, disinfection using UV light follows the familiar CT concept (disinfectant concentration times contact time). However, instead of using CT to describe UV disinfection, UV dose is used instead. UV dose is defined as the measurement of the energy per unit area that falls upon a surface. UV dose is the product of UV intensity, I, and exposure time, T (IT), similar to the CT concept. UV intensity is usually expressed as mW/cm^2 and exposure time is measured in seconds (s). So UV dose is reported as mWs/cm^2. However, UV dose is commonly expressed as millijoules per square centimeter (mJ/cm^2), because 1 mWs = 1 mJ.

Estimating UV Dose

When disinfection test data is not available models can be used to gain an understanding of disinfection capabilities of UV-using IWPDs. Several complex models have been developed to estimate UV intensity delivered to a microorganism. With the estimated UV intensity, the UV dose can calculated based on various exposure times and compared to UV doses determined in scientific literature. The simplest model used to estimate UV intensity is the radial model:

$$I(r) = (P_L / 2\pi r) \times (e^{-aer})$$

Where: P_L = UV power emitted per unit arc length of the lamp (mW/cm)
r = Radial distance from the lamp (cm)
ae = Base e absorption coefficient of the water (1/cm). $ae = 2.303 * A_{254}$
I(r) = UV intensity (mW/cm^2) at a distance r from the lamp

Using data provided by the manufacturer on UV power emitted (P_L), dimensions of the IWPD UV reactor, and assuming water quality variables to develop an absorption coefficient (ae), UV intensity can be calculated. In the absence of good quality IWPD specific testing data, this model can be used to provide a rough evaluation of disinfection capability.

Mechanism of UV Disinfection

Inactivating Versus Killing Microorganisms

When discussing UV light disinfection capabilities, a distinction must be made between inactivating and killing microorganisms. For chemical disinfectants (e.g., chlorine, chlorine dioxide, iodine), inactivating and killing can be considered synonymous terms since chemical disinfectants destroy and damage cellular structures which interferes with metabolism, biosynthesis, and growth. In contrast, UV light does not destroy or damage cellular structures. Rather, UV light prevents microorganisms from reproducing. Microorganisms that cannot

reproduce cannot infect and are thereby inactivated. Subsequently, when evaluating UV disinfection capability, *Giardia* cyst and *Cryptosporidium* oocyst assays that measure infectivity, not viability must be used. Excystation assays measuring viability are not accurate indicators of UV disinfection capability.

Inactivation Mechanism

UV light inactivates microorganisms by damaging deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). When DNA and RNA absorb UV light, damage results from the formation of dimers (covalent bonds between the same nucleic acids). Dimers cause faults in the transcription of information from DNA to RNA, which in turn results in disruption of microorganism replication. The microorganism continues to live, but it can't reproduce and therefore is not infective. A microorganism that cannot replicate cannot infect a host. Microorganisms developed two mechanisms to repair damage caused by UV light. These mechanisms are termed light and dark repair. It is possible for microorganisms to repair themselves to the extent where they will become infective again after exposure to UV light. Fortunately, however, most data indicates UV doses typically used in water treatment prevent most repairs. In general, microorganism inactivation by UV light follows first order reaction rates. However, inactivation rates can vary depending on microorganism type, and water quality conditions (e.g., turbidity, particulate matter, and clumping of microorganisms). Lastly, similar to chemical disinfectants and the CT approach to disinfection evaluation, data has shown that UV disinfection follows the law of reciprocity over an intensity range of 1-200mW/cm^2. For example, a UV dose of 1 mW/cm^2 for 200 sec (i.e., 200 mJ/cm^2) achieves the same level of inactivation as a UV dose of 200mW/cm^2 for 1 sec (i.e., 200 mJ/cm^2).

Environmental Effects

Introduction

UV light can interact with materials potentially reducing disinfection capability. Interactions include absorption, reflection, refraction, and scattering. Absorption is the transformation of light to other forms of energy. When UV light is absorbed, it is no longer available for disinfecting microorganisms. The remaining interactions, reflection, refraction, and scattering, change the direction of UV light and the light is still available for disinfection. UV transmittance and UV absorbance are two related common water quality parameters used to measure these interactions. UV transmittance (UVT), particle content, and constituents that foul lamp sleeves are the most significant water quality factors impacting UV disinfection capability. Water temperature and pH do not generally have an impact on UV disinfection capability.

Effect of UVT

Both UVT and UV absorbance describe the amount of UV light passing through water. They are related by the following equation:

$$\% \text{ UVT} = 100 \times 10^{-A254 * d}$$

Where: UVT = UV transmittance at a 254 nm and a 1 cm pathlength
A_{254} = UV absorbance at 254 nm based on a 1 cm pathlength (unitless)
d = distance from UV lamp (cm). When measuring UV absorbance, d = 1cm

UVT is affected by turbidity, particulate matter, and natural organic matter (NOM). UVT directly affects dose-delivery, and subsequently disinfection capability. As turbidity increases, UVT decreases and UV absorbance increases. Decreased UVT decreases UV intensity delivered to the microorganism, thereby decreasing disinfection capability. Table 1 illustrates the effect of turbidity on UVT, UV absorbance, UV intensity, and the required exposure time necessary to achieve a UV dose of 5 mJ/cm^2 (reference 3). Notice as turbidity increases, UVT decreases, UV Absorbance increases, and UV intensity decreases. Therefore, to maintain a consistent 5 mJ/cm^2 dose, exposure time must be increased. UV absorbers in typical source waters include humic and fulvic acids, other organics, metals (e.g., iron), and anions (e.g., nitrates, sulfites). Both soluble and particulate forms of these compounds will absorb UV light, subsequently reducing UVT. UVT and UV absorbance will vary over time due to changing concentrations of these compounds. UVT and UV absorbance are more variable in rivers and small lakes and will also vary seasonally. Water systems using coagulation/flocculation, filtration, and oxidation treatment processes will increase UVT by reducing UV absorbing compounds, thereby increasing UV disinfection capability. For water systems considering the use of UV disinfection, UV should be installed after filtration. Installing UV prior to filtration will require higher UV doses to achieve the same level of inactivation due to higher levels of NOM, turbidity, and particulate matter. Particles can reduce UV disinfection capability by absorbing UV light and shielding microbes from UV light. No clear correlations have been observed between the amount of turbidity, its characteristics, and the impact on UV disinfection capability (reference 4). Some studies have demonstrated that turbidities above 10 nephelometric turbidity unit (NTU) and even up to 100 NTU have no impact on UV disinfection (references 1 and 5). While other studies observed reduced UV disinfection capability at turbidities in the 5 NTU range (reference 4). In general, increasing turbidities result in decreasing UV disinfection capability. One study showed increasing turbidities from 0.25 to 20 NTU resulted in a 0.8-log and 0.5-log decrease in inactivation of *Cryptosporidium* and *Giardia*, respectively (reference 3). The type of particle present in water can affect UV disinfection. Particles with higher organic content were observed to protect particle-associated viruses from UV light compared to particles of the same size with no organic content (reference 6).

Table 1. Effect of Turbidity on UVT, UV Absorbance, UV Intensity, and Exposure Time.

Turbidity (NTU)	% UVT	UV Absorbance	UV Intensity (mW/cm^2)	Exposure time necessary to achieve 5 mJ/cm^2 dose (s)
0.25	86	0.07	0.40	12.4
5.0	78	0.11	0.39	12.8
10.0	71	0.15	0.36	13.9
20.1	59	0.23	0.33	15.0

Effect of Water Temperature and pH

An advantage of UV disinfection over chemical disinfectants is that inactivation is generally independent of water temperature and pH. Overall, effect of water temperature is insignificant on UV disinfection capability. Temperature can affect the activity of repair enzymes and nucleic acid configuration, which may result in a very slight increase in UV dose necessary with decreasing temperatures to achieve the same log inactivation. Compared to turbidity, particulate matter, and NOM, the effect of water temperature is insignificant. The water pH has an insignificant effect on UV disinfection capability. Repair and nucleic acid configuration are affected by pH. However, pH within a cell is relatively constant and does not vary with water pH. Studies using MS2 virus showed pH over 6-9 range had no effect on inactivation.

Effect of Fouling Contaminants

Fouling of UV lamps will reduce UV disinfection capability. Hardness, alkalinity, temperature, iron concentration, and pH all influence fouling. Compounds exhibiting decreasing solubility with increasing temperatures (e.g., $CaCO_3$, $CaSO_4$, $FeCO_3$) are prime contributors to lamp fouling. One study showed at total and calcium hardness levels less than 140 mg/L and iron less than 0.1 mg/L, mechanical cleaning (wiper sweeping) every 15 min to 1 hour during operation of a continuous flow UV reactor was sufficient to overcome impact of sleeve fouling. The Langelier Saturation Index and Calcium Carbonate Precipitation Potential can be used to help indicate fouling potential by indicating the tendency of the water to form a calcium carbonate precipitate. For UV-using IWPDs, fouling of the UV lamp is not expected to be significant. Although groundwaters are primarily associated with high hardness and dissolved solids, there are also surface waters containing high levels of hardness and dissolved solids (reference 7). Most IWPDs would likely be used with surface waters. However, since IWPD use would be intermittent, not continuous, and the same source would likely not be used consistently, UV lamp fouling is not expected to be a significant factor reducing UV disinfection capability.

Bacteria, Virus, and Protozoa Inactivation Capability

Microorganism Inactivation Capability

The effectiveness of UV light on microorganism inactivation varies with different types of microorganisms. Generally, UV light is most effective at inactivating *Cryptosporidium* and *Giardia*, followed by bacteria and then viruses:

Cryptosporidium and *Giardia* > Bacteria > Viruses

Interestingly, UV resistance appears to follow microorganism size, with the smallest microorganisms being most resistant. The reason for this may be due to the amount of UV light absorption per cell. With microorganisms larger than 1 micron, the absorption of UV light by the cell can be significant, effectively reducing resistance to UV disinfection. Table 2 is a summary of numerous UV disinfection studies and shows UV doses and corresponding log inactivation for various microorganisms. The most UV resistant viruses of concern in drinking water are adenovirus Type 40 and 41. Because viruses are the most resistant to UV disinfection, dosing is controlled by log inactivation requirements for viruses, not protozoan cysts (reference 4). As Table 2 shows, *Cryptosporidium* and *Giardia* are very sensitive to inactivation by low doses of UV light (reference 8).

Table 2. UV Dose and Corresponding Log Inactivation by Microorganism.

Microorganism Type	Microorganism	UV Dose for 3-log inactivation (mJ/cm^2)	UV dose for 4-log inactivation (mJ/cm^2)
Virus	Adenovirus Type 40	90	120
Virus	MS2	52	71
Virus	Poliovirus Type 1	23	30
Virus	Hepatitis A	15	21
Spore	*Bacillus subtilis*	61	78
Bacteria	*Salmonella enteriditis*	9	10
Bacteria	*Salmonella typhi*	5	9
Bacteria	*Escherichia coli*	6.7	8.4
Bacteria	*Vibrio cholerae*	2.2	2.9
Protozoa	*Cryptosporidium parvum*	<6	-
Protozoa	*Giardia lamblia*	<6	-

Adapted from reference 2.

Development of UV Dose Tables

Pursuant to the Long Term 2 Enhanced Surface Water Treatment Rule, the EPA proposed UV dose tables for various log inactivation of viruses, *Cryptosporidium*, and *Giardia* (reference 9). The proposed UV doses for 3-log *Giardia* and *Cryptosporidium*, and 4-log virus inactivation are shown in Table 3. Comparing these doses to those in Table 2 shows that the EPA proposed UV doses are higher. These doses are more conservative and were developed to account for uncertainty associated with the inactivation studies of microorganisms in controlled conditions using low turbidity water (less than or equal to 1 NTU). These uncertainties are addressed by applying a safety factor to experimentally determined UV doses. The EPA collected UV inactivation research data conducted over the past 50 years for adenovirus, *Giardia lamblia, Giardia muris, and Cryptosporidium parvum.* Adenovirus was evaluated because it is considered the most resistant to inactivation by UV light of the pathogenic waterborne viruses. The EPA evaluated 19 studies for these microorganisms. When evaluating UV-using IWPDs that are treating raw, unfiltered waters, higher UV doses than those shown in Table 3 may be necessary to achieve the same level of inactivation. Higher UV doses can be achieved by longer exposure time, removing UV absorbing components (e.g., particulate matter, NOM) from the water prior to UV exposure (e.g., filtration or carbon absorption), or, if possible, increasing UV lamp intensity. Even at higher UV doses, it appears that a UV-using IWPD can reasonably achieve minimum 6-log bacteria, 4-log virus, and 3-log *Giardia* and *Cryptosporidium* inactivation. For example, treating a turbid water (e.g., 30 NTU) may require a doubling of the EPA proposed UV dose of 186 mJ/cm^2 required for 4-log virus inactivation shown in Table 3 (i.e., a UV dose of 372 mJ/cm^2) to assure adequate inactivation. Assuming the UV-using IWPD delivers an average UV intensity of 0.5 mW/cm^2, an exposure time of 744 seconds (~12 min) is necessary to achieve the required dose.

Table 3. Proposed UV Dose Requirements for 3-log *Cryptosporidium* and *Giardia* Inactivation and 4-log Virus Inactivation (mJ/cm^2)

3-log *Cryptosporidium* inactivation	3-log *Giardia* inactivation	4-log virus inactivation
12	11	186

UV TOXICITY

Disinfection Byproduct Formation

A main chronic health concern with chemical disinfectants is the formation of disinfection byproducts (DBPs). Trihalomethanes and haloacetic acids, the only regulated DBPs are not formed during UV disinfection. However, there are studies that show low-level (i.e., ug/L)

formation of non-regulated DBPs (e.g., aldehydes). The health effects of non-regulated DBPs at the levels formed during UV disinfection has not been widely researched. Use of UV-using IWPDs may result in higher levels of non-regulated DBPs formed since raw, unfiltered waters would contain higher amounts of DBP precursors (e.g., NOM). However, the IWPDs would be used on a short-term basis (i.e., < 3-4 weeks) by healthy adult soldiers. Therefore, exposure to UV-produced DBPs would likely have negligible adverse health effects.

Mercury Exposure

There is a health concern for the potential of mercury exposure due to lamp breakage. As discussed earlier, all UV lamps contain some amount of mercury. Lamps used in water treatment systems reportedly have between 5-400 mg of mercury. The risk associated with a mercury release to the water due to lamp breakage during operation depends on many factors. Little information exists regarding the fate of mercury released to the water as a result of UV lamp breakage. This adds to the uncertainty of the risk of adverse health effects. UV lamp breakage during operation can result in potential ingestion of mercury. The EPA established a maximum contaminant level (MCL) for mercury at 0.002 mg/L. The EPA has found mercury to potentially cause kidney damage from short-term exposures at levels above the 0.002 mg/L MCL (reference 10). UV lamps in IWPDs will contain mercury. Since these IWPDs will most likely utilize LP lamps due to lower power requirements and lower operating temperatures, breaking a UV lamp during operation could result in 5-50 mg of mercury being released into the water being treated. Therefore, there is cause for concern, even for short-term exposure of mercury to healthy soldiers if a UV lamp breaks during operation.

CONCLUSIONS

UV Disinfection Capability

UV disinfection is effective against protozoan cysts, bacteria, and viruses. UV light does not kill microorganisms. Rather, it damages the DNA and RNA and prevents the microorganism from reproducing. When a microorganism cannot reproduce it cannot infect. UV light is most effective against *Cryptosporidium* and *Giardia* followed by bacteria. UV light is least effective against viruses. Turbidity, particulate matter, and NOM are the most significant water quality parameters having the greatest effect on UV disinfection capability. Water temperature and pH have an insignificant effect on UV disinfection capability. Increasing levels of turbidity, particulate matter, and NOM absorb more UV light, making less UV light available for disinfection. Similar to the CT concept, the IT concept [UV intensity (mW/cm^2) times exposure time (s)], commonly referred to as UV dose (mJ/cm^2), is used to describe UV disinfection capability. Increasing concentrations of turbidity, particulate matter, and NOM require higher UV doses in the form of increased UV intensity and/or longer exposure times to achieve the same amount of inactivation. Studies evaluating UV disinfection capability indicate UV doses of 120 mJ/cm^2 are adequate to achieve 4-log virus inactivation of the most resistant viruses. The

EPA adds a safety factor and proposes a UV dose of 186 mJ/cm^2 for a 4-log inactivation of viruses. These UV doses will ensure a 3-log *Giardia* and *Cryptosporidium* inactivation and likely ensure a 6-log bacteria inactivation. Most UV lamps used in drinking water applications contain mercury. There is concern of adverse health effects to the consumer as a result of mercury exposure from UV lamp breakage during operation.

Evaluating UV-Using IWPDs

UV-using IWPDs can be effective against *Cryptosporidium*, *Giardia*, bacteria, and viruses. Since raw, unfiltered waters will be treated, UV doses higher than those proposed by the EPA will likely be required to achieve the same level of inactivation. For example, treating a highly turbid water (e.g., 30 NTU) may require a doubling of the EPA proposed UV dose of 186 mJ/cm^2 required for 4-log virus inactivation (i.e., a UV dose of 372 mJ/cm^2). Assuming the UV-using IWPD delivers an average UV intensity of 0.5 mW/cm^2, an exposure time of 744 seconds (~12 min) is necessary to achieve the required dose. This seems reasonable and practical for field use. Models can be used to help understand UV disinfection capabilities of UV-using IWPDs under various water quality conditions likely to be encountered. There is cause for concern for adverse health effects from exposure to mercury if the UV lamp is broken during operation. Since all UV lamps contain mercury and UV-using IWPDs most likely utilize LP lamps due to lower power requirements and lower operating temperatures, breaking IWPD UV lamp during operation may result in up to 5-50 mg of mercury being released into the water being treated. The risk of adverse health effects from UV lamp breakage during operation is uncertain, however, there is cause for concern, even for short-term exposure of mercury to healthy soldiers. Table 4 summarizes UV disinfection capabilities, environmental effects, and potential health concerns with using UV light.

Table 4. UV Disinfection Capabilities.

Parameter	UV Disinfection
General Disinfection Capability	Viruses most resistant. *Giardia* and *Cryptosporidium* least resistant. UV dose will be based on virus inactivation.
Bacteria	Effective at reasonable UV doses for IWPD use.
Viruses	Effective at reasonable UV doses for IWPD use. Use proposed EPA UV dose table for recommended doses (Table 3). UV doses higher than those recommended may be necessary based on turbidity, particulate matter, and NOM.

Giardia Cysts	Effective at reasonable UV doses for IWPD use.
Cryptosporidium Oocysts	Effective at reasonable UV doses for IWPD use.
Effect of Temperature	Negligible effect.
Effect of pH	Negligible effect.
Effect of Turbidity/Particulate Matter/NOM	Significant effect. Higher concentrations require higher UV doses to achieve same levels of inactivation.
Health Effects	UV lamp breakage during operation may exposure user to unsafe levels of mercury.

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APPENDIX A
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